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MODELING THE SURFACE AND INTERIOR STRUCTURE OF COMET NUCLEI USING A MULTIDISCIPLINARY APPROACH

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C. R. O'Dell, Principal Investigator
Department of Space Physics and Astronomy

Panos C. Dakoulas, Co-Investigator
Department of Civil Engineering

George M. Pharr, Co-Investigator
Department of Mechanical Engineering and Materials Science

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ABSTRACT

We have investigated in detail the properties of a model comet nucleus composed of an icy-dust soil. The thermal properties are predicted and related to the observable phenomena seen in the many comet comae and the fly-bye images of Comet Halley. A thorough review of the literature on this subject was made and reported upon in this document.

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I. RELEVANCE OF THIS WORK TO NASA

The mission of NASA includes the execution of space science and exploration of the solar system. Our work falls into both categories since it is essential to the planning of exploratory missions to know as much as possible about the objects beforehand, so that optimal and successful spacecraft can be planned. Comets play an essential role in understanding the origin and structure of the solar system because they represent material that has been little altered over the multiple billions of years of the existence of the planets. This statement was more a statement of faith than substantiated fact until the last decade when a flurry of activity on comets was generated as a response to the Soviet and European flight of spacecraft through Comet Halley in 1986. We now have ample evidence that the inherently bright, long period comets represent molecular conditions generated only in the interstellar molecular clouds which give rise to formation of stars like our Sun. We now also have proof that the comets were formed in conditions of the proto-planetary system that were never significantly heated and since the gravitational pressure of these small bodies is very low, they were not physically processed as were the much larger planets. All of this new information strengthens the arguments for a comet intercept mission, a need fulfilled by the CRAF (Comet Rendezvous and Asteroid Fly-bye) mission.

II. THE STANDARD MODEL OF THE NUCLEUS

The standard model for the nucleus of comets was generated from inferential data beginning in 1950 (1) and given an enormous boost from the Comet Halley fly-throughs. In this section we will first discuss the pre-1986 model and then consider the changes due to Comet Halley.

Essentially all of the mass of a comet resides in its nucleus, the solid body of a few kilometers radius. At a characteristic distance of one AU this subtends an angle of only 7 milliarcseconds, a full order of magnitude beneath the resolution limit of the Hubble Space Telescope, our most powerful imaging instrument. The problems of this small angular size are compounded by the fact that when a nucleus is close enough to subtend even this small angle it is surrounded by a bright coma of fluorescent gas and dust scattering particles. For these reasons it has been extremely difficult to study the nucleus directly and almost everything we know has been derived inferentially from study of the material that forms the coma and tail of the comets, this material having recently escaped from the low gravitational field of the nucleus.

As a comet approaches the Sun the surface temperature of the nucleus rises above that characteristic of the periphery of the solar system where they have been in cold storage in the Oort Cloud. As solar energy is absorbed frozen gases on and near the nucleus' surface are sublimated, with the more volatile gases starting to emit at lower temperatures (greater distances), being joined by the less volatile at higher temperatures until by the time the region of the terrestrial planets is reached all molecules are being sublimated and the rate of liberation is simply determined by the total amount of energy being absorbed (2). Once into the gaseous form the thermal velocity of the gas is a few kilometers per second and since this is vastly greater than the few meters per second escape velocity of the surface of the nucleus, the gas freely expands into space, carrying with it through viscous drag any small particles in the nucleus that were freed in the process of sublimation of the gases. This model of the processes occurring at and near the surface of the nucleus infers that the nucleus must be a solid body composed of a mixture of frozen gases and dust. Detailed studies indicate that there are about equal mass fractions of each. This model is generally known as the dirty snowball, although the icy dustball might be more descriptive. The atomic composition of the nucleus is determined from spectroscopic studies of the coma to be the same as the Sun with the possible exception of Iron (3).

Photometry of the nucleus has noted periodic variations in the brightness, indicating that the nucleus is variable in its amount of reflected light. This means that the nucleus is usually either variable in its reflecting properties and/or that it is not spherically symmetric (4). Interpreting the periodicities in the brightness changes to indicate stable rotation one derives periods of a few hours to a few days, the former values meaning that the rotation speeds approach the velocity of escape. Further knowledge about the physical nature of the nucleus comes from the fact that numerous comets have been observed to break up (5), the cause of which is probably the differential effects of solar gravity on the two sides of the comet, from which one derives a very low tensile strength.

The non-homogeneity of the nucleus is further verified by the fact that we often see structures in the coma indicating that gas and dust is coming from areas small compared with the hemisphere illuminated by the Sun (6). These "hot-spots" are probably the sources of light that move into and out of the field of view to produce the variations in photometric brightness. They indicate that the nucleus is irregular.

This basic picture changed very little from the Comet Halley fly-throughs, although much of what was previously conjectural could be put onto solid ground. The greatest surprise to many was the low reflective albedo of only about 3% (7) and the low bulk mass density of about 0.2-0.6. This means that the dirty snowball is actually very un-compacted and that the surface material has probably been darkened through long term effects of ultraviolet radiation and cosmic ray bombardment. The elongated nature of the nucleus was confirmed as was the presence of several hot-spots which give rise to most of the material in the coma. The surface was found to be highly irregular at scales of 0.1 the diameter. The atomic abundances basically did not change but the studies of the dust were more surprising. Mass spectrometer analysis of the particles impinging the spacecraft revealed two broad classes of chemical compositions, the first being like chondritic meteorites and the second being primarily H, C, N. and O, and are called the CHON particles. There was an unexpected rich population of very and fragile particles, some of which broke down just before hitting the spacecraft (8).

The fly-throughs produced some surprises and put much of our inferential knowledge onto a more solid basis, but they still were inferential about the nucleus itself. We know that the gases escaping the nucleus interact with one another in a chemical soup that alters the molecular composition from that at the surface of the nucleus (9) and the original and created molecules rapidly break down into simpler molecules and atoms under the effects of solar photodissociation(10). What is needed to truly determine the nature of the nucleus is a comet visit mission that includes direct sampling and study of at least the surface material.

III. CURRENT AREAS OF RESEARCH

The bulk of the observational work on comets deals with the coma because it is easily observed and can reveal information indirectly about the nucleus. There have been no recent revelations about the basic processes occurring, but the compilation of results from different comets allows study of the characteristic evolution of the nucleus. Comets have an enormous range of periods, most being greater than the historic record, so little information exists about the change of individual comets. Rather inhomogeneous data over past millennium indicates that Comet Halley is slowly decreasing in absolute brightness and there is some evidence that a few short period comets are slowly disappearing. In general a single comet has been observed only once during the era of quantitative imaging. This means that current research investigates comets of opportunity, then derives their illumination history by the Sun from backwards calculation of their earlier orbits, then the comet is placed into an evolutionary scheme. The result that is developing is that the nuclei becomes intrinsically less luminous with time and that the ratio of emission of gas and dust changes in the sense of relatively more gas being lost from "older" comets. The details of these studies include the search for new molecular species (10) and observational resolution of the relative roles of chemical reactions and photodissociation in the inner coma surrounding the nucleus (11).

A. Thermal Cycling of the Nucleus

Significant progress in improving our understanding of the thermal history and structure of cometary nuclei has been made during the last decade. This progress is based on new information regarding cometary material and activity, as well as on experimental data on the thermal behavior of such materials. A common description of the nucleus is as a low density ice ball consisting of crystalline ice which is enclosing a larger mass of amorphous ice in the interior. (There is some evidence that at least part of the nucleus material is amorphous ice, the existence of which would require a temperature below 85 K.) The exterior of the nucleus is probably a layer of dust forming an insulating crust. This crust may consist of particles with size ranging from micrometers (dust) to several centimeters. (Centimeter sized particles may be agglomerates of smaller particles bonded with various ices. Similar centimeter sized agglomerates form clouds that orbit around the nucleus (12). At the active areas of the crust, there is an outward jetting of gases.

Due to their different thermal properties, crystalline ice and amorphous ice demonstrate quite different patterns of behavior during the thermal cycling processes in the nucleus. Indeed, the conductivity of crystalline ice decreases with temperature, while the conductivity of amorphous ice increases (13,14). Porosity reduces conductivity to 20-30% of that of solid ice, for density estimates similar to those in Halley's comet. In addition, one has to consider the gas conductivity, which at temperatures above sublimation may increase the conductivity of porous ice to levels similar to that of solid ice. Experiments simulating heating of the nucleus dust mantle resulted into water vapor produced in the interior transporting heat very efficiently (15). Such heat transport by vapor may be important even at low temperatures ($\geq$50 K), as shown from laboratory data on amorphous ice (16).

Using such experimental data for the material behavior, attempts for numerical modeling of the response of comet nuclei approaching the Sun have been made, by considering various assumptions regarding the main phenomena affecting the response. Such numerical models can demonstrate the combined effects of the assumptions related to the physical properties of the material (e.g., porosity), the chemical composition, the heat diffusion through the solid material, the gas diffusion, and possibly the radioactive heat generation.

During perihelion, the comet nucleus surface may be heated to temperatures well above the crystallization threshold temperatures. As a result, a surface layer of crystalline ice is formed after the first passage and is deepened with every new passage. This layer is experiencing sublimation of H_2O, CO, CO_2 and other volatiles in the crystalline ice. Beneath this layer, there is amorphous ice, which has a lower temperature and is richer in volatiles. The release of trapped gas and the sublimation of volatiles results in transfer of latent heat in two opposing directions: mainly outwards to the nucleus surface (convection), but also partly towards the interior of the nucleus (advection) followed by recondensation. After many passages near the Sun, a very substantial part of volatiles is lost from the surface. The observed gas in the active areas is mainly from the interior. It is reasonable to expect that the remaining solid particles and volatiles form a highly porous structure. The strength of this porous material may be attributed to the same type of inter-particle forces that appear in low-strength clay with very low water content and a highly porous structure. For example, such bonding may be due to hydrogen bonding, Van-der Waals' forces, and other types of chemical bonds. As the pristine amorphous dust-ice mixture comprising the nucleus was more likely to be heterogeneous rather than homogeneous and experiencing various degrees of sublimation, the "de-icing" nucleus may show substantial strength differences at various areas. When weak surface areas are subjected to a peak level of heating from the Sun at perihelion, they are likely to be the first to produce active areas with craters and outgassing. For Halley's comet nucleus, these active areas cover about 10% of the surface. The continuous erosion of the surface from the volatiles is bound to weaken its structure and result into breaking to small peaces in the form of dust, centimeter sized agglomerates or even larger peaces of the surface. This breaking (which may occur in a continuous or discontinuous manner) may result in a gradual settlement of the surface of the nucleus at every passage near the Sun. Since only a small portion of the solid particles is leaving the nucleus compared to the portion of the volatiles, it is more likely that solid particles will accumulate on the surface forming the crust (or dust mantle). In time this mantle will increase in thickness. As more volatiles are sublimated from the underlying layers of crystalline and amorphous ice, patches of weakened material beneath the dust mantle may settle by slow creep or collapse abruptly, leading to collapses of the overlying dust mantle, and thus modifying the surface topography and creating craters. Alternatively, weakly supported portion of the mantle subjected to internal gas pressures may be blown off. Such collapses or blows may allow easier exits for the outgoing gases and, in time, develop permanent main arteries through which the gases will find their way to the surface. However, as the mantle thickness increases, it would tend to insulate better the interior and, therefore, the temperatures in the interior and the sublimation rate would tend to decrease gradually. Although the presence of the dust mantle will affect significantly the temperature and sublimation rate near the surface, computations by Herman and Weissman (17) showed that it has very small effect on the interior temperature (only about 1 K). It should be noted that the argument about the presence of the dust mantle is strongly supported by the existence of distinct active areas on the nucleus surface and by the very minor outgassing, if any, from the rest of the surface.

In addition, a possible scenario, which is not in contradiction with the above and for which there is some corroborating evidence, is based on the radioactive decay of ^{26}Al. Indeed, ^{26}Al in a relative abundance of at least 10-8 may produce enough heat to be able transform the amorphous ice to crystalline starting from the center of the nucleus and expanding outwards in the form of a crystallization front, which eventually will reach the nucleus surface (18). Temperatures of 125 to 137 K may develop at the crystallization front (19) due to crystallization latent heat. Such temperatures in the crystallized interior of the nucleus would result in significant outgassing of volatiles similar in nature and quantity with those observed in various comet nuclei. The radioactive heat combined with the additional surface heat at perihelion, may reach critical temperatures that will intensify the surface activities (brightness and outgassing) in accord with the actual observations.

The thermal cycling of the nucleus (due to its periodic passage near the Sun) and the related observed phenomena may be of significant importance in developing a better understanding of the material properties of the nucleus. Indeed, among all factors producing stress in the nucleus, namely, self-gravitation, rotational centrifugal force, tidal forces during close encounters with planets or the Sun, and thermal gradients, the latter appears to be the most important one in developing maximum stresses within the nucleus (20). The splitting of a about 25 comets during the last 140 years, most of them (with few exceptions) during perihelion, is strong evidence for assessing importance of the above stress producing factors. Although few of them may be attributed to the rest of the factors, the majority may be due to thermal stresses. Outbursts often occurring during pre-perihelion or post-perihelion may be due to either splitting of the nucleus or simply breaking of small part of the dust mantle, caused be increased internal gas pressure. A challenging task is the derivation of the periodic thermal profiles and the corresponding thermal stresses developed as the comet approaches perihelion. To this end, Fanale and Salvail (21, 22) developed a model for calculation of the nucleus insolation history, the water and dust flux, the dust mantle thickness and stability, and the distribution of temperature with depth, by considering the gas production and diffusion. Squyres et al. (23) used a one-dimensional model for heat conduction to compute the periodic thermal profile, by considering heat transport through radiation and Knutsen flow along a porous ice. Horanyi et al. (24) developed periodic temperature profiles as a function of the mantle thickness, by considering a "friable sponge" model. This model assumes that the dust is ejected only from the surface and not from the interior of the nucleus. (The latter may be in contradiction with the fact that a minor portion of the gas is ejected through the inactive surface to justify the significant total dust to gas ratio ejected.) Houpis et al. (25) introduced the effects of different chemical processes due to different temperatures within the nucleus. As a result several mantles are formed in the nucleus, having different compositions, physical and thermal properties and temperatures. Tauber and Kuhrt (26) used a simple water ice nucleus to model the variation of thermal stresses. Their findings provided new insight in understanding possible mechanisms causing outbursts and intensified jet activity. Green (20) used a series of numerical models to calculate transient thermal stresses within the nucleus by considering various characteristics of the porous structure of the icy materials of the nucleus. In particular, the thermal conductivity, specific heat, coefficient of thermal expansion, Young's modulus and Poisson's ratio were modeled as functions of the porosity, by using a three-phase composite material model. A parametric study was undertaken in which the thermal conductivity was modeled numerically as a function of the porosity, pore shape, pore size, ice and pore vapor composition, pore orientation, pore size distribution, pore packing geometry, particle interface size and the heat transport mechanism. Two-dimensional simulations of the nucleus surface layers at thicknesses of 60 m and 250 m produced temperature and thermal stress profiles, as functions of the porosity, pore shape, and the presence or absence of pore vapor. The thermal stresses were used to examine the possibility of fracture, by using linear elastic fracture mechanics of crack propagation. Green found that the porosity and the size, shape, and orientation of the pores have a significant effect on the thermal conductivity and, therefore, on the thermal stresses, which are function of the thermal gradient, the temperature, and the elastic properties. Moreover, she found that prior passages of the comet through perihelion, cause compression of the material, and she concluded that this may lead to stronger material and reduced thermal stresses. Thus the possibility of fracture after many passages becomes less likely. (Considering the fact that at post-perihelion there is tension developing on the crust, with the possibility of cracking, the previous conclusion may not be valid.) Finally, she concluded that prior perihelion passage would also result in the increase of the insulating dust mantle, and therefore, to a reduction of the thermal stresses within the nucleus. In the case of heterogeneous nucleus, intense heat and stress concentrations may lead fracture.

The above findings may be used to develop a better understanding of the phenomena controlling the generation of outbursts, jets, and the splitting of comet nuclei at or close to perihelion. As a comet approaches perihelion, the surface temperature increases rapidly, since the conductivity in the interior is low due to the low temperature. Hence, the thermal gradient is high and thermal stresses develop near the surface and attenuate rapidly with depth. As the comet comes closer to the Sun, the temperature of the nucleus increases further, and therefore the conductivity too. This leads to more efficient heat transport, which is increased even more when the vapor conductivity is added. Then, the surface temperature is increasing at a lower rate, as more heat is transported in the interior, resulting to a smaller heat gradient and, therefore more uniform stress distribution with depth. The thermal stresses developing as the comet approaches perihelion and at perihelion are compressive. It is not unlikely that such compressive stresses, combined with material heterogeneities and surface irregularities, may result to a buckling failure of a portion of the surface, thus exposing more pristine and volatile richer material, and initiate the dynamic process for the generation of an active region on the nucleus surface. Such buckling blow off may be significantly helped by the internal gas pressures which increase as vapor action intensifies. As the comet leaves the Sun at post-perihelion, the temperatures on the surface drop much faster than those in the interior. This results to the development of tensile thermal stresses that may lead to substantial cracking of the crust. Such cracking will allow an easier escape for the sublimating gases in the near region of the nucleus. Thus, again, it may initiate the dynamic process for the generation of an active region on the nucleus surface.

OTHER ACTIVE AREAS

An alternative dust mantle model based on observations on the gas production in the active areas of Halley's comet nucleus and corresponding computations by Huebner et al. (27) of sublimation in these areas using simple energy balancing equations suggest that the production of such gas may be local. However, the observed velocity of the gases may suggest rather significant gas pressures which may lead to the opposite conclusion that, gas is produced through sublimation of a larger mass of the nucleus, as discussed above.

Attempts to correlate the production and sublimation with brightness, lead to the conclusion that brightness, although correlates well with the production curves of C_2 and CH, it does not correlate with the production of OH (28).

Sekanina (28) produced water sublimation curves calculated for a spherical nucleus in a heliocentric orbit with a perihelion distance of 1.5 AU corresponding to many short period comets. Water production rates observed on Comet Encke from 1971 to 1987 show very good agreement with this model.

An area of interest is the development of a better understanding of outbursts. A number of hypotheses were introduced over the years to explain the existence of outbursts. Whitney (30) and Huebner (31) considered the existence of pockets of highly volatile material, Donn and Urey (32) assumed exothermic chemical reactions, Harwit (33) considered collisions with interplanetary boulders. Patashnick et al. (34) suggest the phase transition from amorphous ice (at temperatures below 140 K) to crystalline ice. Later studies by Smoluchowski (35) supported this hypothesis. More recent studies by Prialnik and Bar-Nun (36) showed that such a phase transition may release significant energy and that some of the gas trapped in amorphous ice may accumulate in a pocket, which under certain conditions may explode. Jewitt (37) used the same concepts according to which sudden exposure of the subsurface amorphous ice triggers outbursts. Correlations between comet splitting sand outbursts were reviewed by Sekanina (38).

IV. APPROACH OF THIS RESEARCH ACTIVITY

The study of comets has evolved significantly in this century. During the first half it was primarily the province of celestial mechanicians and spectroscopists. The breakthrough made by Whipple (1) in developing the dirty snowball model was the direct result of combining these two areas. Once it was understood that the nucleus was a single solid component there began a series of articles considering the possible properties, this work was done almost exclusively by persons trained in astronomy and lacking the background information for treating with solids. We have tried to overcome this limitation by convening a team of three scientists, an astronomer (O'Dell) quite experienced in observational studies of the coma and the author of previous papers on the possible origin of comet nuclei, a materials scientist (Pharr) experienced in the properties of frozen matrices of material, and a civil engineer (Dakoulas) who specializes in the study of soils. The latter two were particularly relevant because we know that the nuclei are frozen solids and that they are composed of a mixture of poorly compacted dust and frozen gas.

Our goal has been to investigate the structural properties of the surface of the nucleus and how the surface should change with time under the affects of solar radiation. The basic model that was adopted was that the nucleus is an aggregate of frosty particles loosely bound together, so that it is essentially a soil. This approach is very different from most investigations. For example, a recent Ph.D. thesis from the University of Texas assumed that the nucleus was a frozen solid having small voids and imbedded solids (20). Such a model cannot be correct because we now know that the bulk density is significantly less than unity. This probably reflects the fact that the nuclei have such low gravitational fields that little compaction occurs. Moreover, we know that the nucleus must mostly be composed of dust particles. The observed mass ratios of dust to gas in the coma is never much greater than unity, but this ratio is probably a much lower limit than that of the nucleus because it is vastly easier to remove the gaseous component by sublimation than by carrying off the dust. Therefore our models assumed that the particles in the soil were frost covered grains of submicron basic size, closely resembling the interstellar grains, a position argued for from several different angles by others (39). We sought to generally characterize the surface properties of such a nucleus under the effects of heating and cooling as the nucleus approaches and recedes from the Sun.

V. CRITIQUE OF CURRENT WORK OF OTHERS

The same epoch that marked the recognition of the true basic nature of the nucleus (1) also revealed why we still see comets even though the luminous lifetime of all comets is much shorter than the age of the solar system. The mere fact that we see the comae indicates that gas and dust is being lost from the nucleus with the best estimates being a loss of about 0.01-0.1% of the total mass at each perihelion passage. This would not be a problem for the very long period comets that have characteristic periods of 10's-100 million years but is a serious obstacle to explaining the presence of the most frequently seen comets with periods of a few hundred years. The latter objects should have died long ago. Oort (40) showed that the most frequent orbits were those of very high eccentricity and long period and that the shorter period comets were simply that small subset that had successfully been gravitationally "captured" by successive passages through the inner solar system. The important bottom line of this model is that explanation of the number of comets that we actually see demands that there is a reservoir of billions of comet nuclei at average distances of greater than 10,000 AU. This model is very attractive since it can explain the existence today of these relatively volatile objects. However, it is very difficult to understand how nuclei could have formed at such large distances from the Sun. This means that the standard model requires formation of the nuclei from the same planetesimals that formed the major planets (the distances must have been beyond Saturn or most of the gases present would have be lost), and then gravitationally perturbed into long period orbits with perihelia distances near the zone of formation, then circularization of the orbits into the Oort Cloud. For us to now see the objects require them to have been reperturbed into more eccentric orbits that come back into the planetary system. The principal drawback of this model is that very few of the nuclei should have survived. The initial perturbation by the major planets will largely produce hyperbolic (escape) orbits, as would the perturbations that circularize the orbits of a few, as would the perturbations that cause a few to come back into the inner solar system. This daisy chain of unlikely events demands an untenable number of comets in the original solar system and we are now seeing the need by the modelers to compromise the Oort Cloud concept by adding an Inner Oort Cloud (41) and then even more recently a closer in "Kuiper Belt" of much shorter period comets (42) which circumvent the low probabilities of the Oort Cloud model. There are so many band-aids on the model that the time seems ripe for an alternate explanation.

The possible link of comet nuclei and some asteroids has become a more distinct possibility. It is now understood that there are orbital similarities (43) in some cases and we know that most of the asteroids are very low albedo, highly irregular objects like the comets, but of course they are larger or we would not see them at the distance of the asteroid belt. Perhaps the "missing link" has already been found in the form of the giant asteroid Chiron. For several decades it fit nicely into the asteroid classification but more recently it has been found to be undergoing emission of material of the same type as comet nuclei at the same distance (44). There now seems to be little doubt that at least a portion of the asteroid population represent nuclei that have become so inert on their surface that no visible exosphere is seen. If this is indeed the case, then we would expect them to be covered with a soil of devolatilized particles, probably of interstellar origin.

VI. RESULTS FROM OUR STUDIES

A. Strength Information from Break-ups

It is of interest to estimate the strength of the nucleus material, by examining the causes of breakups or non-breakups. It is reasonable to assume that the solid particles and volatiles which form the highly porous structure of the nucleus have a the strength which may be attributed to the same type of inter-particle forces that appear in low-strength clay with very low water content and a highly porous structure (hydrogen bonding, Van-der Waals' forces, and other types of chemical bonds). As the pristine amorphous dust-ice mixture comprising the nucleus was more likely to be heterogeneous and subjected to various degrees of sublimation, the nucleus dust-ice may show substantial variations in its strength.

As mentioned above, the most important factor contributing to significant stresses within the material is the thermal processes occurring as the comet passes near the Sun. Indeed, if one considers the self- gravitational forces, for Halley's comet nucleus which has an oblate shape with a large axis 2a=16 km, a small axis 2b=8 km and an estimated average density ρ = 300 kg/m^3, the acceleration of gravity is easily computed from a closed-from solution equal to about 3.5×10^{-4} m/s^2 at the surface along the large axis and 4.2×10^{-4} m/s^2 at the surface along the small axis. Such very small gravitational accelerations will produce very small static stresses within the nucleus. Thus, at depth z (m) from the surface point along the short axis the normal stress in the direction of the short axis will be about

$$\sigma_1 = g\,\rho z = 4.2 \times 10^{-4}\ m/s^2 \times 300\ kg/m^3 \times z = 0.12z\ N/m^2$$

The normal stress in the tangential direction σ_3 at the same point, may be computed by extending soil mechanics principles for "geostatic conditions," where this stress will be about half of the value of σ_1. This leads to a maximum shear stress at the point equal to

$$\tau = (\sigma_1 - \sigma_3)/2 = 0.03\ z\ N/m^2$$

As opposed to thermal and tidal forces, the gravitational forces act always on the comet nucleus. Therefore, if the nucleus preserves its solid oblate shape, this means that the developing shear stresses due to self-gravitation are smaller than the shear strength of the nucleus material. Otherwise, the oblate shape would be transformed to a sphere after failure of the material in shear (just as if the nucleus consisted of a liquid). At depth z (m) the shear strength, s, may be expressed with the Mohr-Coulomb failure criterion $s = c + s \tan\phi$, where c is the cohesion, ϕ is the angle of internal friction of the material and σ is the normal stress on the failure plane. To preserve a constant oblate shape, $s > 0.03\ z\ N/m^2$. This condition sets a lower limit to the material strength. By considering the gravitational tidal torque at perihelion another lower bound of the strength may obtained if no braking takes place. In this case, the strength s is found $s < 0.002\ N/m^2$, which generally give values much less than the previous value (and therefore is neglected).

An upper bound for the material strength may be obtained by considering the collapse of portions of the slopes or wall of existing active craters. For a collapse of a piece about 100 m to take place due to its weight, the strength of the material can be roughly estimated through stability considerations about 4-6 N/m^2. This assumes that near the crater there is a crack already (perhaps due to prior thermal irregularities in the area). If no such crack exists or if the pieces are smaller than 100 m, the estimated strength is less than the above estimate. However, such estimate depends entirely on the assumption that no other factors, such as thermal stresses are responsible for the collapse. The latter may not be true. Indeed, for expected temperatures on the nucleus surface of about 250 K at a distance 1.3 AU (20), the strength of a corresponding porous water ice with density about 300 Kg/m^3 is about 20-30 kN/m^2 (G), which is four orders of magnitude higher than the above estimates. Therefore, it is reasonable to assume that most likely other factors, such as thermal stresses, may be the reason for slope failures and the expansion of active areas.

B. Expected Thermal Properties Near the Surface

Estimates about the temperature and thermal stress distribution with depth in the comet nucleus can only be obtained through numerical simulations. Such results are presented by Green (20) for a comet in a P/Halley orbit and at distances 2.6 AU to 1.3 AU at pre-perihelion. The results were given for a three-phase material with various porosities varying from 0 to 50%. The computed temperature profile appears to be independent of the porosity and is more critical for the case of no vapor action, since then the conductivity is less and the thermal gradient maximum. The results show an almost linearly decreasing temperature profile, with a maximum temperature of 250 K at the surface and 163 K at a depth of 23 m from the surface. The corresponding tangential stresses are maximum at the surface and equal to 7 MPa for 50% porosity (52 MPa for 25% porosity and 100 MPa for 0% porosity). Such compressive stresses are much larger than the value of ultimate unconfined compressive strength which, for ice porosity of 50%, is about 1 MPa (45). However, the value of the compressive stresses are extremely sensitive to the assumption regarding the porosity. An extrapolation of the almost linear relationship of compressive strength and porosity given by these results, suggests orders of magnitude smaller stresses at porosities above 60%. It appears that a porosity about 60% to 70% is more consistent with the corresponding strength of porous ice. In this case, it is expected that the thermal stresses, although much smaller than the above values, will still play an important role in explaining the observed phenomena.

At post-perihelion, as the nucleus moves away from the Sun the rapid cooling of the surface combined with a much slower reduction of the interior temperature, leads to the development of tensile stresses near the surface, and, when the tensile strength is exceeded, to cracking. These cracks may expand due to jetting of sublimating gas and thus become large enough, so that during the next pre-perihelion passage they may not close under the pressure of the pre-perihelion compressive stresses. Open cracks at this stage may initiate new dynamically expanding active areas through excessive sublimation and erosion.

Concluding, the assumptions regarding the material porosity become extremely critical to the development of meaningful conclusions.

C. Explanation of Outbursts as Slumping Phenomena

From the diverse conditions and the various forms of their appearance, it is clear that outbursts are not due to a single mechanism (46,47). One possible mechanism may be the slumping of the edges of craters and the exposure of new pristine material in the form of crystalline or amorphous ice to higher temperatures and sublimation. Such slumping may be caused from compressive thermal stresses on already cracked and weakened masses of crust material during the pre-perihelion stage. It appears that by considering a material porosity in the range of 60% to 70%, the corresponding porosity dependent strength properties and thermal stresses would yield values that may explain convincingly the contribution of slumping phenomena to the outburst observations. The slumping process may be greatly accelerated by undermining of the wall of the active region by the exposure of pristine amorphous ice with significant amounts of trapped volatiles to the Sun radiation, leading to an almost explosive sublimation.

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INVENTIONS AND PATENTS

In compliance with NASA requirement, we report that there were no inventions or patents on this work.